# HOLISTIC WINTER MAINTENANCE MODEL

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**Topic 2: Costs and benefits of winter service in a constrained budgetary context**

## ABSTRACT RÉSUMÉ

From the road users point of view the main purpose of winter maintenance is providing a high level of accessibility and skid resistance at all times. Faced with a growing demand in winter maintenance quality the personnel is in a difficult situation to decide about treatment intervals as well as application rates and timing. With limited time for decision making during treatment cycles and fast changing environmental factors even expert drivers with vast experience might not be able to arrive at optimal decisions. Based on the combined efforts of all regional road authorities in Austria as well as ASFiNAG and BMVIT a holistic model for winter maintenance was developed at the Vienna University of Technology. With this new model all relevant factors from temperatures, precipitation rate, type of de-icing agent, application rate and traffic volume as well as road surface condition can be accounted for. As a result it is both possible to calculate a resulting skid resistance based on any given application rate as well as timing and necessary application rate in order to provide a certain level of road friction in real-time. The model parameters have already been determined based on a series of partly new developed laboratory and field tests. Among these tests where high precision laser scans to determine road texture volume as well as film thickness tests and friction – measurements at various times during winter maintenance. Combining this model with already available information about traffic and road surface condition as well as weather now-casts a high resolution forecast for very short road sections on the entire network of highways in Austria becomes feasible. The paper gives an overview of this holistic winter maintenance model together with selected findings from field and laboratory tests as well as an application of these results.

KEY WORDS: numerical modelling, application rates, treatment strategies, optimization

## 1. INTRODUCTION AND OVERVIEW

Winter maintenance is responsible for about 25% of operating costs on highways and up to 30% on federal state roads in Austria. The necessary efforts in winter maintenance as well as the resulting salt consumption are strongly dependent on weather, road conditions as well as a number of other factors and thus fluctuate significantly between winter periods. From the road users point of view these difficulties are not important. What they want are snow and ice free roads with a high level of accessibility and skid resistance at all times in order to arrive safe and on-time at their destination. On the other hand there are technical, ecologic and economic limitations for winter maintenance that have to be considered as well. Altogether this leads to fundamental questions regarding timing and application rates as well as the resulting needs and impacts of different treatment strategies. With the combined efforts of all regional road authorities in Austria as well as ASFiNAG and BMVIT it was possible to conduct several research projects during the last five years in order to answer these questions. The research projects consisted of numerous field and laboratory experiments to determine the relevant input variables and verify the outcomes of a new holistic winter maintenance model [1;2;3].

With this developed model all relevant factors like precipitation type & rate, traffic volume, treatment intervals and application rates, road surface condition and resulting skid resistance are accounted for. Furthermore, the holistic model allows an assessment of ecological and economic impacts for any given weather scenario and winter maintenance strategy. Thus, it is possible to compare different treatment cycles and application rates with the necessary resources and resulting costs. Furthermore, it is feasible to optimize the entire winter maintenance process under any given regulations and preconditions. The research outcomes have already been put to practise leading to a number of training courses and a comprehensive winter maintenance guide that is used on the entire high level road network in Austria [4;5].

However, the focus of this paper is an in-depth view into the developed winter maintenance model together with an overview of the determination of all relevant input factors and a verification of the main results. Figure 1 provides an overview of the developed holistic winter maintenance model with its four core modules residual salt, water film thickness, freezing point and skid resistance. The logistical framework, the cost components and the environmental impacts are additional parts of the presented model. The necessary detailed information regarding these topics are beyond the framework of this paper and may be found in the project reports [1;2].

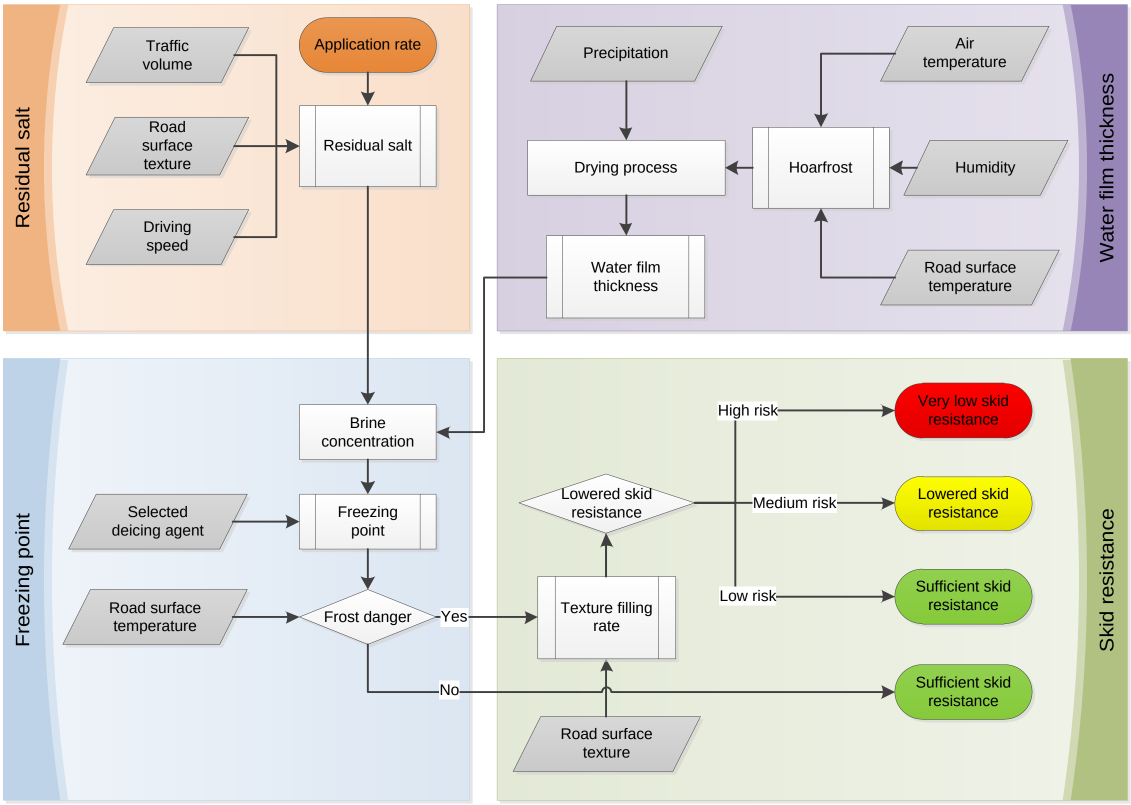


Fig. 1: Winter maintenance model developed at the Vienna University of Technology

The module residual salt consists of the input parameters traffic volume, road surface texture and driving speed of winter maintenance vehicles with the input variable application rate of de-icing agents. Starting from any point in time with a new treatment cycle a certain amount (5 to 40 g/m$^2$) of pre-wetted salt is applied. Depending on road conditions, wind and driving speed initial discharge losses have to be considered as well as on-going losses due to scattering and drainage effects. The amount of residual salt thus shows an initial drop during the first five to ten minutes and an asymptotic decrease thereafter until the next treatment cycle. For an on-going calibration of this module both a real time monitoring of treatment cycles as well as continuous sensor measurements of residual salt are recommended.

The module water film thickness consists of both monitoring and prediction of precipitation events as well as emerging hoarfrost. The resulting water film thickness on the road is therefore a function of time and precipitation rate as well as possible drying processes due to drainage, evaporation and traffic. Due to the amount of water usually not exceeding 50 to 100 g/m$^2$ between 2:00 to 5:00 am hoarfrost is in most cases not critical if a preventive treatment of 5 to 10 g/m$^2$ of de-icing agent is applied. Snowfall-events or freezing rain occur less often, but usually bring higher amounts of water on the road affecting the amount of residual salt leading to a decreasing brine concentration on the road surface with on-going precipitation. Both water film thickness and brine concentration can be calibrated based on punctual measurements from fixed sensors or optical longitudinal sensor measurements that may be conducted during treatment cycles.

The residual salt and the water film on the road are forming a brine with the freezing point being a result of selected de-icing agent and brine concentration. A freezing process only occurs if the road surface temperature drops below the freezing point of the brine. The road surface temperature can be modelled based on air temperature and albedo with a distinction between clouded precipitation days and days with clear sky. An on-going calibration of predicted road surface temperatures is also feasible based on punctual sensor measurements and mobile measurements with winter maintenance vehicles. For a consistent modelling of resulting road conditions and optimal treatment strategies the duration of freezing and thawing processes have to be considered as well. If the water film is already frozen the road will have a low skid resistance during the whole thawing process. A freezing process takes also time and may be delayed due to a (preventive) treatment leading to a higher amount of remaining skid resistance during that time.

Whether or not a freezing process is leading to a lowered friction is covered in the module skid resistance. As long as there is no freezing process obviously the skid resistance will be in line with values from standard measurements under wet conditions (RoadStar, Griptester) usually exceeding a critical value of $\mu \geq 0{,}4$. In such cases there are usually no restrictions except in cases of danger from aquaplaning which can be assessed based on rut depth or spray fountains from vehicles. If a freezing process occurs the resulting skid resistance is lowered, if the pavement texture is filled to a certain amount so that the tyres lose their contact to the pavement. The resulting skid resistance is therefore a function of initial skid resistance and texture filling rate if freezing already occurred. The calibration of both texture volume and existing texture filling rate respectively thickness of freezing water film can be performed based on fixed or mobile visual sensor measurements as well.

The following sections of the paper provides an overview of the main input parameters together with their functional dependency based on empirical verified regression functions. Due their empiric nature and unobserved local factors some of the regression functions show a somewhat wide distribution around the mean. From the perspective of short individual road sections this may lead to deviations between model results and local conditions. Thus all results of the holistic winter maintenance model need an on-going calibration of input parameters and results as described above. Due to the central limit theorem and the averaging effects of road conditions during long braking distances these local deviations are not that critical. Further strategies to cope with these deviations may also include a probabilistic calculation using predefined safety margins. However, approaches with tighter safety margins will also lead to higher winter maintenance costs.

## 2. DETERMINATION OF RESIDUAL SALT

The amount of residual salt can be determined both based on fixed or semi-mobile sensor measurements. The fixed sensors can be either passive (conductive principle) or active (cooling below freezing point). The semi-mobile measurements are mainly based on a conductive principle and have been performed in the research projects with the Sobo20. The advantage of Sobo20 are the possibility to measure on several points without the need for wet conditions compared to fixed measurements. For a verification of the impact of road conditions and traffic volume on the amount of residual salt only calibrated Sobo20 measurements were used [1;2].

Figure 2 (a) provides an overview of the average initial discharge losses amounting to around 60% of the total amount of applied pre-wetted salt (FS30). If dry salt (FS0) is used in most cases except a wet road surface the discharge losses are higher. Using brine only (FS100) leads both to a lower total possible amount of salt per square meter and lower discharge losses as well. Thus, brine spreading may be optimal for preventive treatment in case of hoarfrost or light precipitation events whereas it will fall short at low to very low temperatures and high precipitation rates. Figure 2 (b) provides an overview of the on-going losses due to scattering and drainage effects. The losses increase with total traffic volume after treatment and are the highest under wet conditions with dominant drainage effects and the lowest under moist conditions. At dry conditions the losses are somewhere in between due to insufficient adhesion and drift phenomenon’s.

In the modelling process residual salt (RS) can be calculated using Formula 1a for dry conditions, appearing mostly at preventive spreading, Formula 1b for moist conditions e.g. hoarfrost and Formula 1c for wet conditions in case of precipitation. Initial losses are taken into account with 60 % of the application rate (AR), the declining factor is traffic volume (TV) in the reviewed period. For more accurate results the time intervals for calculations should not exceed 10 to 20 minutes and need to be calibrated with sensor measurements.

$$RS = AR*0.4*(-0.00009 * TV + 0.8171) \text{ (dry road, } R^2=0.4437) \tag{1a}$$

$$RS = AR*0.4*(-0.00005 * TV + 0.935) \text{ (moist road, } R^2=0.2718) \tag{1b}$$

$$RS = AR*0.4*(-0.0003 * TV + 0.8009) \text{ (wet road, } R^2=0.2048) \tag{1c}$$

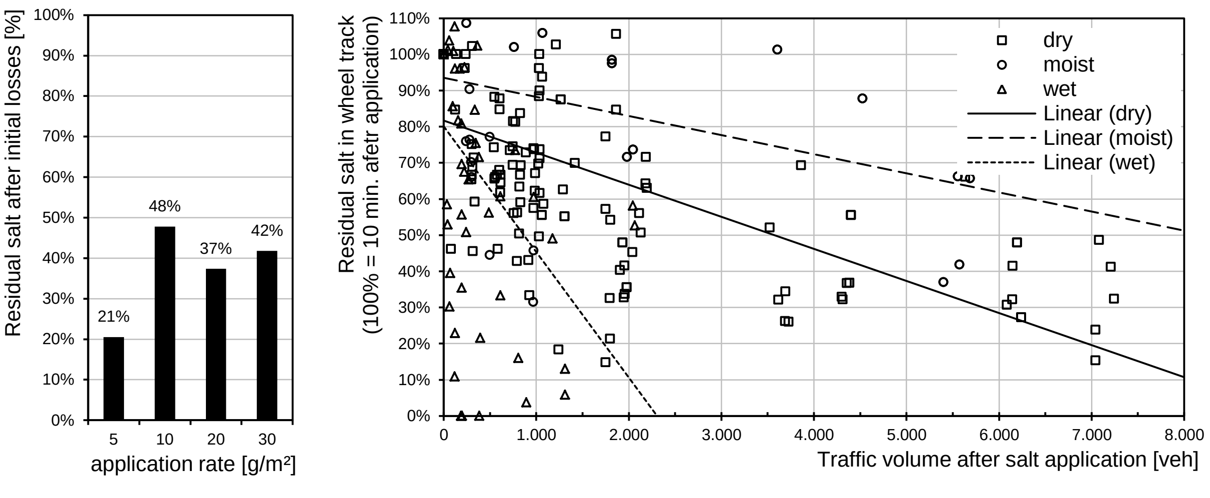


Fig. 2: (a) Initial salt losses after application; (b) Residual salt on the road depending on traffic volume and road surface conditions

## 3. WEATHER, PRECIPITATION EVENTS AND WATER FILM THICKNESS

### 3.1. Verification of air and pavement surface temperature predictions

Weather forecasts are usually more uncertain the longer predictions reach into the future. In winter maintenance it is therefore common practice to use 12 to 36 hour forecasts for scheduling of resources and more accurate short term forecasts of up to 12 hours for scheduling of treatment cycles and generalized application strategies. Finally, local observations of experienced winter maintenance personnel are used for final decisions regarding application rates and further treatment needs. Figure 3 provides an overview of the INCA – webportal with the nowcasts of air and pavement surface temperatures.

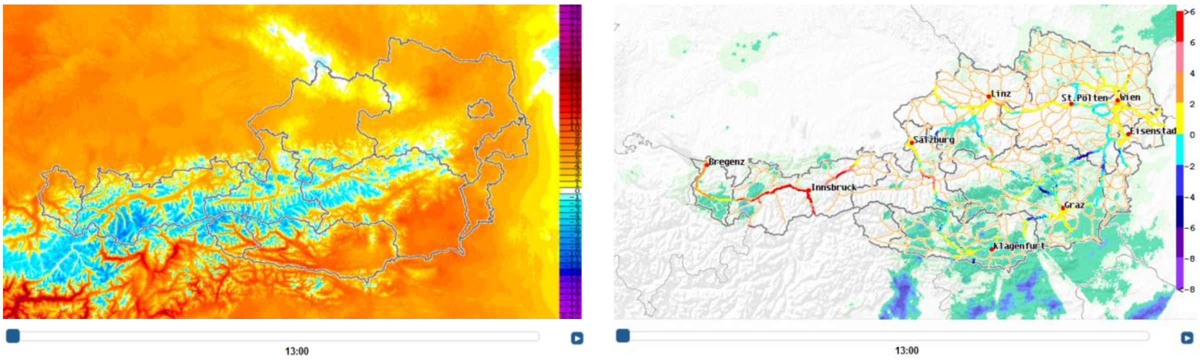


Fig. 3: (a) INCA - nowcast 2m air temperature (b) INCA – nowcast surface temperature

For an assessment of the accuracy of short term forecasts the INCA – nowcasting system [6;7] of the Central Institute for Meteorology and Geodynamics (ZAMG) and a common weather service have been analysed in the research project “Winterfit” [3;8]. Figure 4 provides an overview of air and surface temperature deviations between calibrated sensor measurements and nowcasts of both weather services for one month. The average prognosis value of air temperature is for both services right on the mark with service #1 showing a considerably lower deviation than weather service #2. Regarding the more important road surface temperature weather service #1 predicts in average -1.36°C (σ=±2.01°C) and weather service #2 predicts in average -3.01°C (σ=±2.91°C) lower temperatures compared to actual measurements. Regarding winter maintenance air temperature prediction models provide a sufficient level of accuracy whereas pavement surface temperature prediction models have still improvement potential.

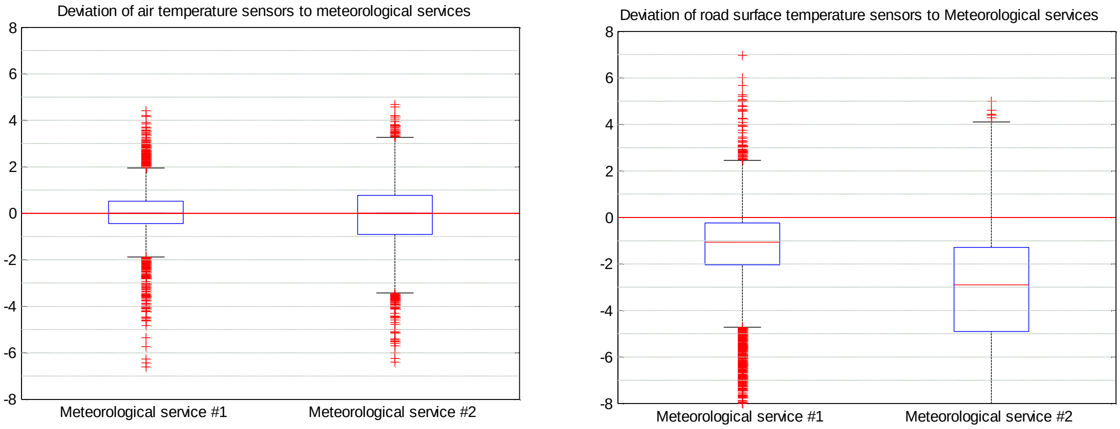


Fig. 4: (a) Air temperature deviation between 2h nowcast and sensor measurement
(b) Surface temperature deviation between 2h nowcast and sensor measurement

### 3.2. Calibration of air and pavement surface temperature predictions

The road surface temperature is related to air temperature and albedo with certain difference between clouded precipitation days and days with clear sky. Based on data from weather stations and pavement surface temperature sensors the development of air and pavement temperature during typical days can be analysed. Figure 5 provides an overview of average air and road surface temperature development as well as the absolute difference between both values during typical winter days for one month from a highway section in Golling. On dry and sunny winter days the pavement surface temperature is usually below air temperature between 0 to 9 am and 3 to 12 pm. Due to solar radiation pavement temperature will typically rise above air temperature between 9 am and 3 pm. On clouded days with and without precipitation the pavement temperature development is almost in line with air temperature development being in average 1°C higher during the day except from 11 am to 3 pm.

For winter maintenance the scenario of dry days with clear and cold nights and low surface temperature is of importance due to a high likelihood for hoarfrost. The limited amount of water in case of hoarfrost leads to a lower necessary accuracy of road surface temperature predictions compared to days with precipitation events because a preventive treatment will be sufficient. On clouded days with precipitation the deviation of road surface temperature from air temperature is typically much lower and the temperature development is more stable. With air temperature nowcasts in most cases being accurate enough a combination with such standardized temperature profiles from punctual measurements could lead to a substantial increase of achieved precision. If these calibrated predictions are combined with longitudinal temperature profiles from mobile measurements an identification of critical road sections becomes feasible as well.

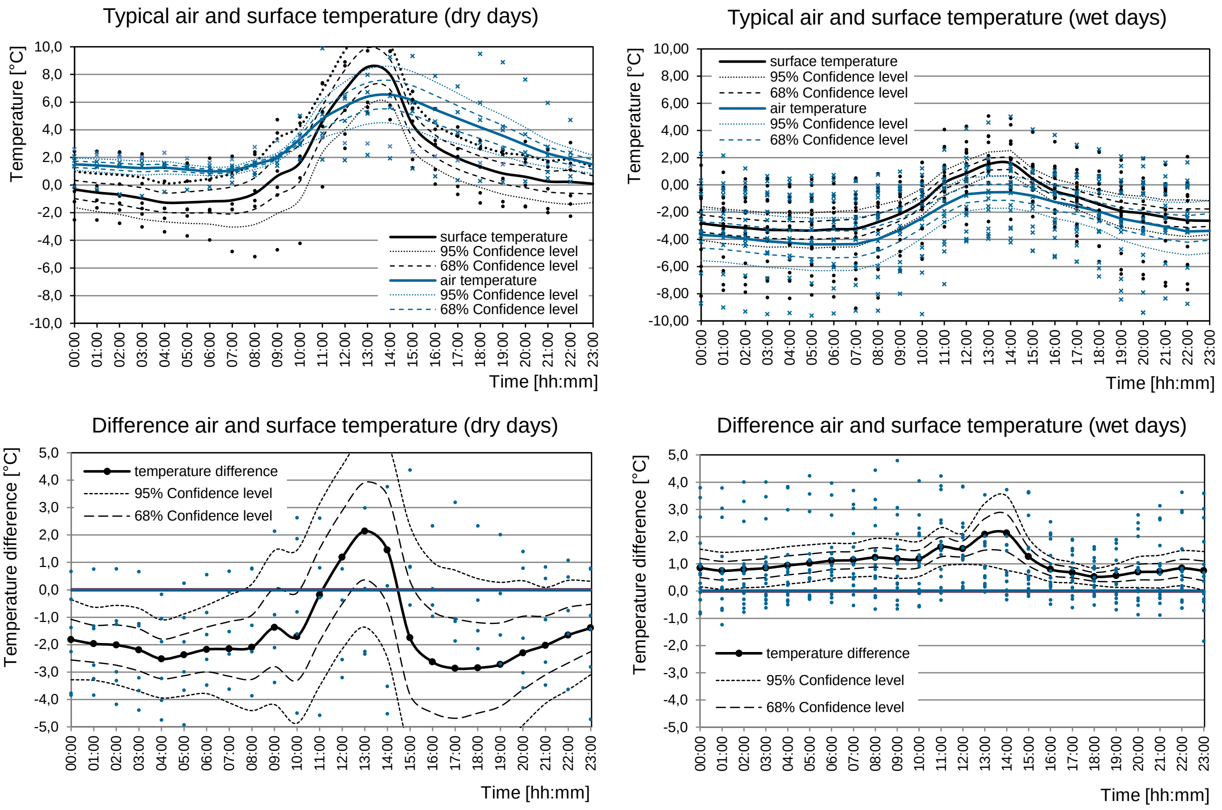


Fig. 5: (a) Typical air and surface temperature development on dry days (Feb. 09)
(b) Typical air and surface temperature development on wet days (Feb. 09)

## 3.3. Prediction and verification of precipitation and snowfall events

The forecasts of precipitation type, amount and timing are also important input parameters for the holistic winter maintenance model. In order to achieve reliable results it is therefore necessary to compare the predicted amount and timing with measured values from weather stations. The accuracy of the predicted amount of precipitation in winter maintenance may be based on a comparison of precipitation rate in a given time frame and total amount of precipitation for a given event. In order to compare the beginning of precipitation events it is necessary to define a winter maintenance related boundary condition. Any precipitation event exceeding a total amount of 0,5 mm precipitation is of potential relevance for winter maintenance due to this precipitation volumes usually leading to texture filling rates with substantially reduced skid resistance if freezing occurs.

In the project “Winterfit” the deviations between predicted and measured total amount of precipitation and timing of precipitation events have been analysed [3;8]. Figure 6 provides an overview of the results from 13 observed events from the winter period 2012/2013. The deviation of the predictions for the total amount of precipitation is still somewhat large with an average of -0.24 mm (σ=±4.74 mm) for weather service #1 and the corresponding values of -0.39 mm (σ=±4.72 mm) for weather service #2. The predicted start of precipitation events is even more off with an average of +1.5 hours (σ=±4.3 hours) for service #1 respectively +2.8 hours (σ=±4.4 hours) for weather service #2. Based on the available amount of data there is a systematic tendency to underestimate the predicted total amount of precipitation and the intensity of precipitation events. Based on the accuracy of the beginning of winter maintenance events from service #1 it is at least possible to define a reasonable time frame with increased alertness. If the weather stations in the area measure a starting precipitation or experienced maintenance personnel observes the start of a precipitation event there is usually still enough time due to initial preparations and the texture reserve to start a new treatment cycle.

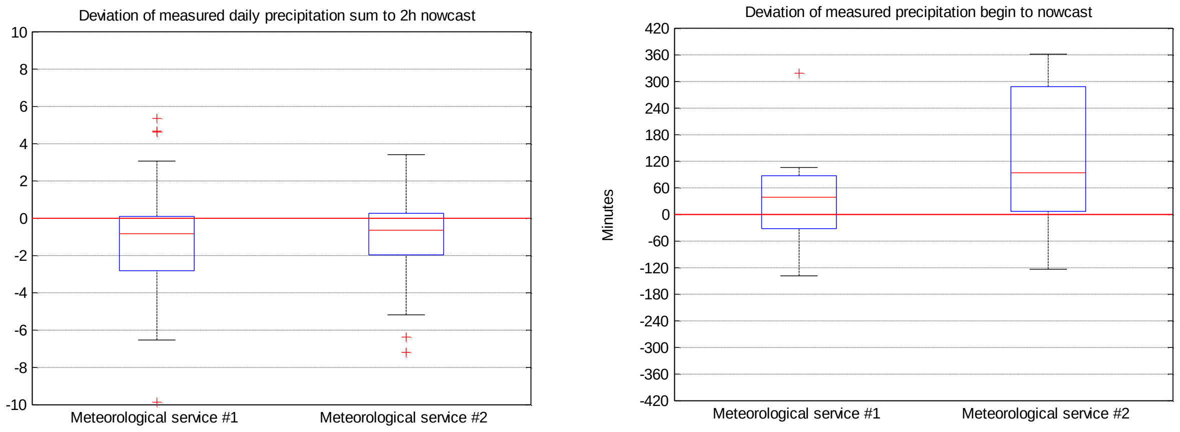


Fig. 6: Deviations from precipitation nowcast (2h) start and daily amount of precipitation and measured data from one independent weather station (n=13)

## 3.4. Frequency of precipitation and snowfall events

The analysis of the frequency of typical precipitation and snowfall events provides the means for an assessment of the occurrence probability of certain scenarios as well as the assessment of total costs if different winter maintenance strategies are employed. Furthermore, it becomes possible to distinguish between rare events with extreme conditions that are hard to tackle and simple unpreparedness for common events. Figure 7 provides an overview of the analysis results for all snowfall event data from all available weather stations from 1st of November 2005 to 31st of March 2010 in Austria. For roads between 0 to 300 m above seal level in average 11.4 snowing days with Ø3.77 cm of snow (respectively 3,77 mm precipitation) are to be expected in an average winter season. This numbers increase to 18.5 (Ø4.89 cm) respectively 25.5 snowing days (Ø6.37 cm) for 300 to 600 m respectively 600 to 900 m above sea level. Extreme weather conditions with a total amount of snow exceeding 10 cm occur statistically only once or twice a year (< 600 m MASL). Snowing days with extreme low temperatures of less than -10°C are even more rare and occur only once every five years.

In general most snowfall events occur at average air temperatures between -3°C and +2°C and tend to be more severe the higher the roads are above sea level. Thus, most snowfall events are in a temperature range with the highest impact of de-icing agents. Based on the available resources for winter maintenance and limited thawing capacity of Sodium Chloride it can be shown, that it is possible to keep the roads free of ice and snow most of the time. However, there will be always rare events where this is not possible purely due to physical reasons. Even if the resources for winter maintenance would be doubled the outcome for road users would not improve much compared to the additional costs.

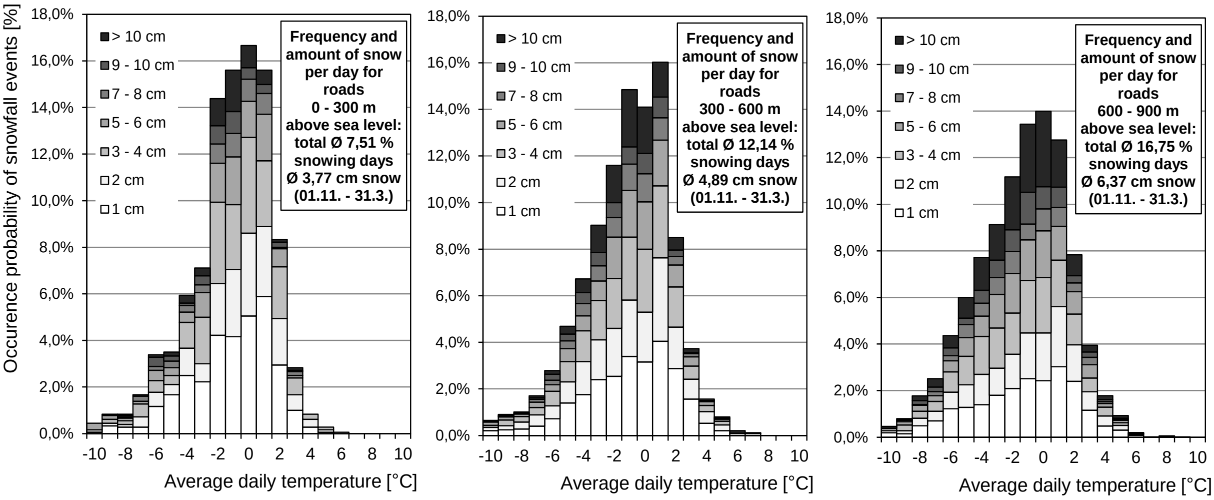


Fig. 7: Probability of snowfall events and total amount of snow per day depending on height above sea level and temperature in Austria

## 3.5. Calculation of water film thickness

If the pavement surface temperature is known, the precipitation film (PF) on the road can be estimated) with Formula 2a [9] using precipitation rate (RR) as basis for a dry up mechanism due to traffic volume (TV) and wind speed (W). At this stage precipitation is calculated based on an equivalent amount of water (1 cm snow ~1 mm water). The different behavior of snowfall consistency and density will be addressed in further in-depth field research. Hoarfrost (HF) is also a source for ice/water on the road and can be estimated using wind speed (W), temperature (T) and the difference between actual vapor pressure and saturation vapor pressure (D) using Formula 2b [9]. All of these predicted input parameters from nowcasts have to be verified constantly based on field measurements in order to achieve reliable results.

$$PF = (RR + HF)*e^{-TV*(0.005+0.001*W)} \tag{2a}$$

$$HF = 2,16*10^{-6}*W*D/T \tag{2b}$$

## 4. DEICING AGENTS, FREEZING POINTS AND THAWING CAPACITY

For common de-icing agents the freezing point decreases with increasing concentration up to a certain eutectic point with no further increase or decrease (Figure 8). The mathematical description in Formula 3a for sodium chloride, Formula 3b for calcium chloride and Formula 3c for magnesium chloride allow a determination of the freezing point (FP) depending on the brine concentration (BC). The formulas have been verified based on extensive freezing experiments [1;2;10].

$FP_{NaCl} = -0{,}001866 * BC^3 + 0{,}03995 * BC^2 - 0{,}8580 * BC - 0{,}3169$ $(R^2=0{,}99)$ (3a)

$FP_{CaCl} = -0{,}001120 * BC^3 - 0{,}007779 * BC^2 - 0{,}4046 * BC - 0{,}3845$ $(R^2=0{,}99)$ (3b)

$FP_{MgCl} = -0{,}002421 * BC^3 - 0{,}000354 * BC^2 - 0{,}5510 * BC - 0{,}4077$ $(R^2=0{,}99)$ (3c)

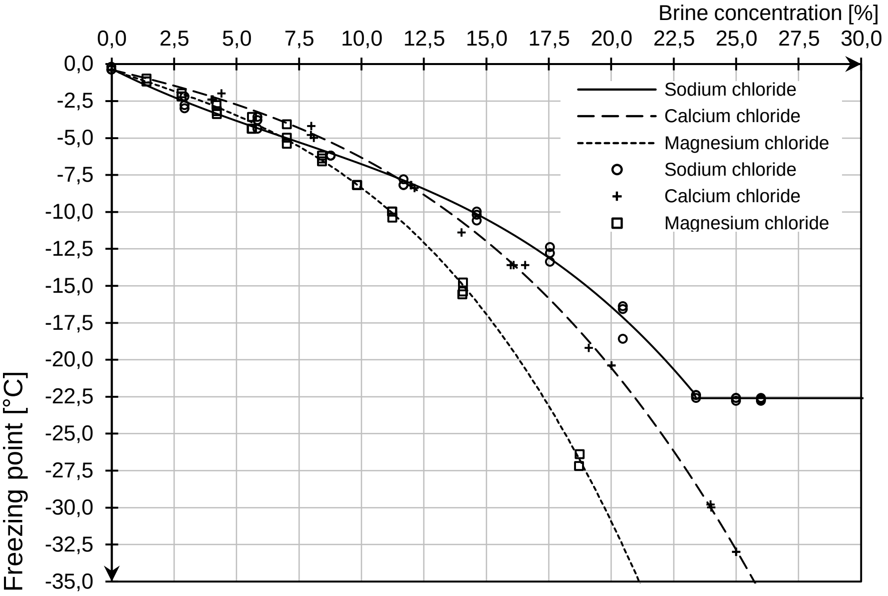


Fig. 8: Freezing point diagram for different brine concentrations of sodium chloride, calcium chloride and magnesium chloride based on freezing experiments

The thawing capacity provides information about the thawed amount of ice versus one unit of de-icing agent. For a fixed amount of de-icing agent applied the thawing speed will be very fast at first due to an initial high concentration and will slowly decrease due to a decreasing brine concentration with an asymptotic development of temperature difference between air/ice temperature and freezing point of the brine until an equilibrium is achieved (Figure 9). The thawing capacity is of high importance because the thawing process takes quite a time limiting the usefulness of treatment cycles shorter than half an hour. As a freezing process takes at least an equal amount of time the usefulness of a preventive treatment prior to freezing is evident. Furthermore, a preventive treatment may form a release coating in cases of continuous precipitation allowing an easier snowploughing and reduced application rates during the next treatment cycle. Formulas 4a to 4c allow a calculation of thawing capacity TC [g] as a function of time t [hours] and air temperature based on extensive thawing experiments with sodium chloride [1;2;10].

$TC_{NaCl}\ (-2.5°C) = 0{,}7961 * t^{0{,}4794}$ $(R^2=0{,}79)$ (4a)

$TC_{NaCl}\ (-5.0°C) = -0{,}3606 * t^{0{,}5697}$ $(R^2=0{,}92)$ (4b)

$TC_{NaCl}\ (-7.5°C) = 0{,}5576 * t^{0{,}3798}$ $(R^2=0{,}87)$ (4c)

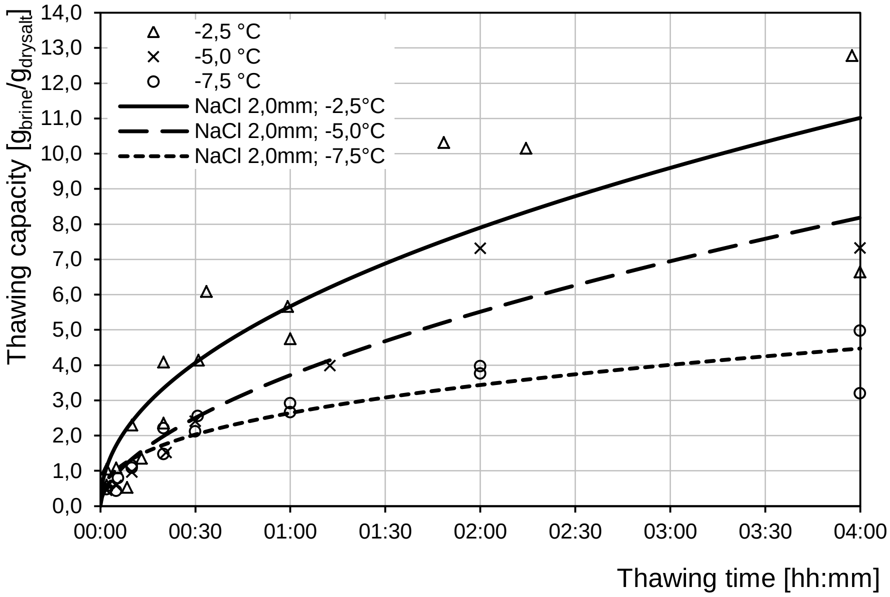


Fig. 9: Thawing capacity of sodium chloride for temperatures -2.5°C, -5.0°C and -7.5°C based on thawing experiments for a grain size of 2.0 mm to 3.15 mm

## 5. PAVEMENT SURFACE TEXTURE AND SKID RESISTANCE

### 5.1. Impact of texture filling rate on skid resistance

The available contact area between tire and road is very limited and has the form of a rectangle with rounded corners. Depending on pavement material and tire tread usually a sufficient level of skid resistance of μ≥0,4 can be achieved even under wet conditions. If freezing occurs the water film will not be liquid anymore leading to a reduced contact are between tire and pavement surface. With increasing amounts of snow or ice on the road the tire will gradually lose contact with the road surface (Figure 10).

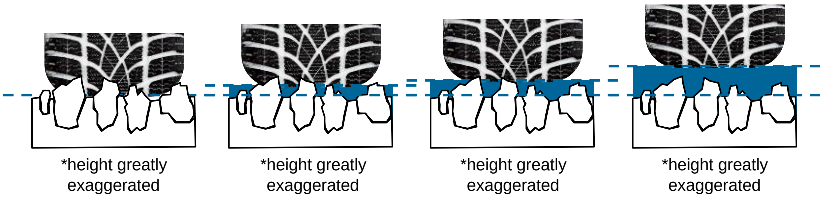


Fig. 10: Reduced contact area tire-road due to filled texture volume with freezing precipitation

In order to avoid only punctual results for texture volume and skid resistance a correlation between exact laser topography scans and already available field measurements have been established (Figure 11). Furthermore an additional relation towards a fast local assessment based on the sand patch method could be established as well [2;11;12].

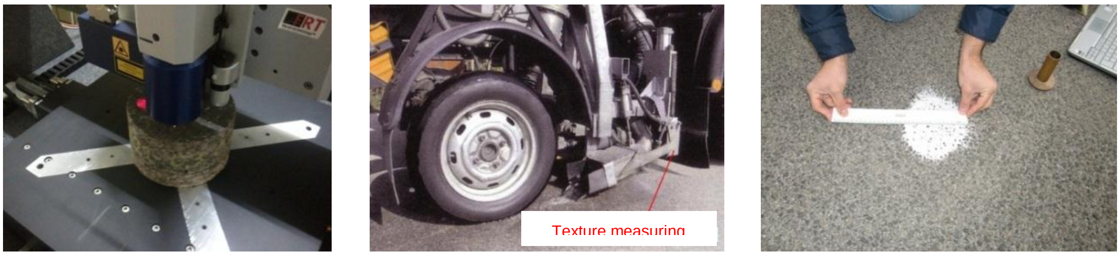


Fig. 11: (a) Laser topography scan (b) RoadSTAR texture measuring device (c) Sand patch method

In the precise 3D-Model the highest peak of the surveillance area is used to calculate the volume compared to the sand patch method with several local peaks determining the diameter of the patch. The linear relationship between these two methods is described in Formula 5a. The sand patch method as a simple, cheap and fast forward field method is suited perfectly for the local determination of road macro texture volume. Formula 5b provides the means to calculate the mean texture depth of the sand patch method based on a 90% single sided confidence interval of MPD – measures being available for the entire network of highways and a majority of regional roads in Austria. Figure 12 provides an overview of these functional relations together with the empiric evidence.

$$V_L=1.335*V_{SP}+101.3 \qquad (R^2=0,98) \qquad (5a)$$

| | |
|---|---|
| $V_L$ | Geometric determined volume (Laser scan) [mm³] |
| $V_{SP}$ | Volumetric determined volume (Sand patch) [mm³] |

$$MTD=1.1354*MPD-0,4685 \qquad (R^2=0,65) \qquad (5a)$$

| | |
|---|---|
| MTD | Mean texture depth (Sand patch) [mm] |
| MPD | Mean profile depth (RoadSTAR) [mm] |

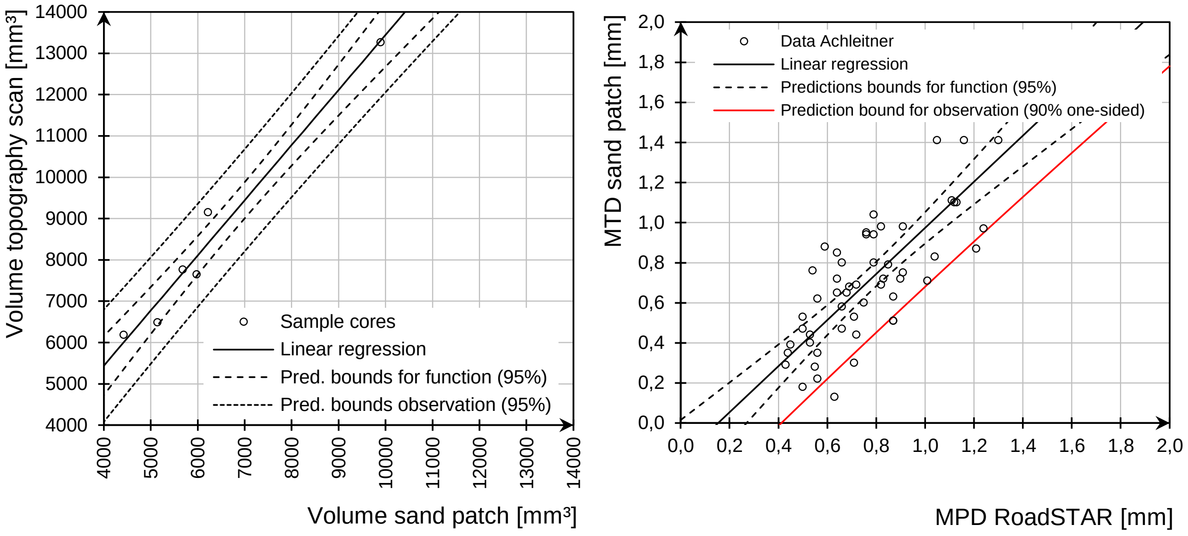


Fig. 12: (a) correlation between volumetric (sand patch) and geometric (topography scan) determined volume n=7 R² = 0.9799 σ=449.7 (b) correlation between MTD (sand patch) and MPD (RoadSTAR) n=53 R²=0.646 σ=0.2231

The wetted surface of road pavements is defined as the liquid surface area in relation to the total area. Based on the 3D – texture from laser topography scans it is possible to establish a relation between wetted surface and macro texture volume based on a stepwise filling of the texture from the lowest point of the surface to the highest peak. Figure 13 provides the results of these calculations for two sample cores A10_G1 and A10_G6 (rigid pavements) compared to the four other cores (flexible pavements). The tested rigid pavements have a considerable higher absolute texture volume due to exposed aggregates. Under the assumption of a constant precipitation rate the time buffer from the time of starting precipitation and a comparable texture filling rate with significantly lowered skid resistance is 60% higher. Especially flexible pavements show a critical drop in available contact area if the precipitation volume exceeds 500 g/m$^2$ (0,5 mm precipitation ~ 0,5 cm snow). Thus, even a constant precipitation rate leads to a sudden drop in skid resistance if the macro texture is filled up to a certain amount.

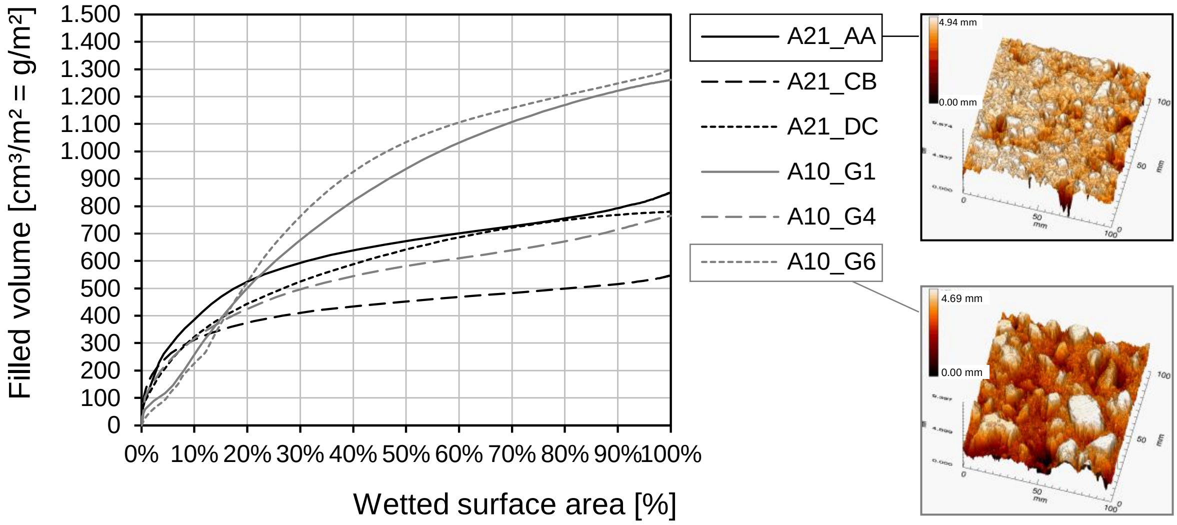


Fig. 13: (a) Correlation: filled volume – wetted surface for 6 sample cores. (b) Topography laser scans of cores A10_G6 (asphalt) and A21_AA (concrete)

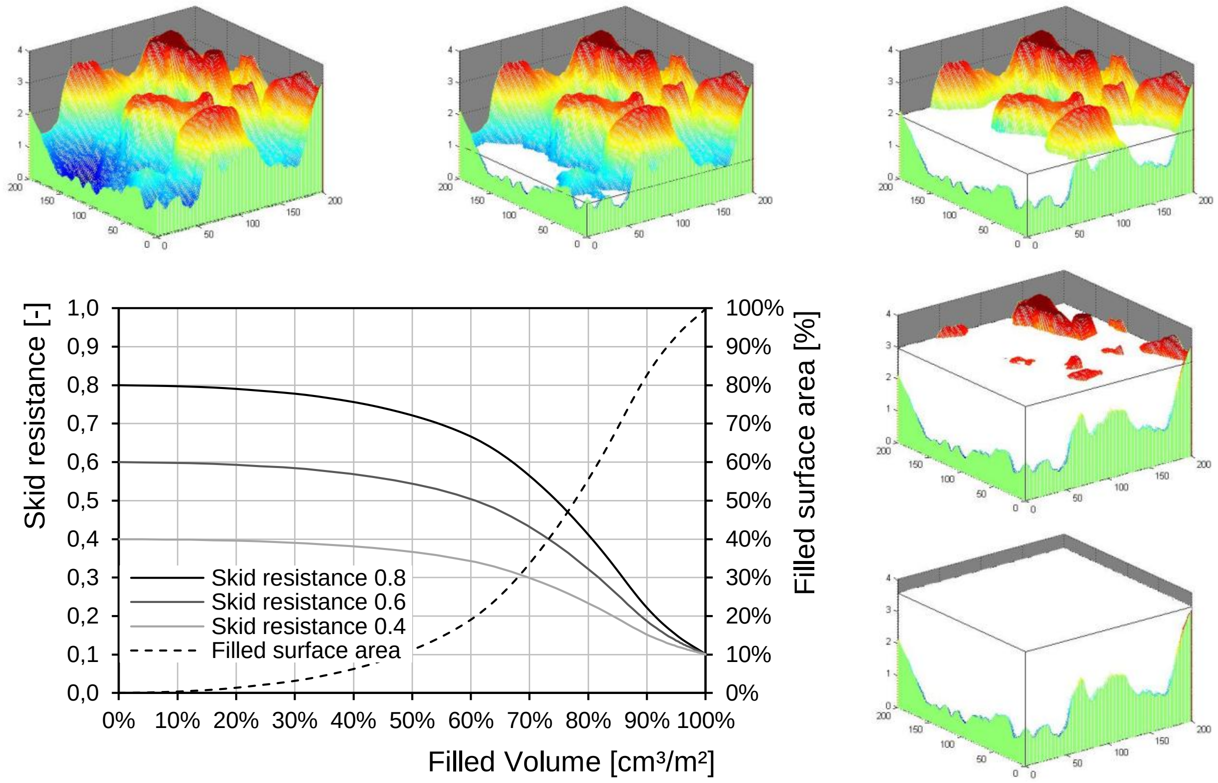


Fig. 14: Example calculation for the resulting skid resistance with freezing as a function of measured skid resistance (wet) based on filled texture volume

As a simple modelling approach the calculated skid resistance is based on an the relative available contact area between tyre, pavement surface and intermediate mediums with their respective characteristic skid resistance values. The three solid lines represent roads with good (0.8), average (0.6) and poor (0.4) skid resistance under wet measurement conditions. With increasing macro texture filling rate the contact area is gradually covered with snow or ice leading to a sudden drop of skid resistance between 60 to 90% of filled macro texture volume. The combined skid resistance in the contact area may then be calculated based on Formula 6.

$$SR = SA_{snow} * SR_{snow} + (100\% - SA_{snow})*SR_{wet} \tag{6}$$

| | |
|---|---|
| SR | Resulting combined skid resistance [ - ] |
| $SA_{snow}$ | Surface area covered with snow/ice [%] |
| $SR_{snow}$ | Typical skid resistance of snow covered roads [ - ] |
| $SR_{wet}$ | Skid resistance of a road under measuring conditions [ - ] |

## 5.2. Verification of water film thickness and skid resistance

The verification of both film thickness and resulting skid resistance was conducted based on extensive measurement runs before and after treatment cycles. For a determination of film thickness and state of freezing process optical measurement devices were used together with a griptester to determine the resulting skid resistance (Figure 15). Further results of the measurement runs on highways may be found in the research reports [2;3].

Fig. 15: Verification of film thickness and resulting skid resistance based on longitudinal measurements with (a) optical device #1 (Vaisala) (b) Optical device #2 (Teconer) (c) Skid resistance (Griptester MK II)

Based on several field measurements the impact of thin snow or ice layers on skid resistance and the development after winter maintenance treatments could be verified. On a first measurement run of the presented example the pavement surface was covered with snow resulting in a skid resistance of 0.13 with a release coating (brine from preventive treatment) of 0.2 mm thickness beneath the snow layer. With the next treatment cycle the snow was cleared and the skid resistance increased to μ=0.37 within 30 minutes after treatment. Continuous snowfall after the treatment thinned the brine until the freezing point was above surface temperature leading to a thin layer of ice and decreasing skid resistance until the next treatment cycle (Figure 16). In general, optical mobile film thickness measurements confirm the relation towards lower skid resistance, but provide significantly lower values compared to calculated texture volume due to a lower resolution and high measurement speed among other factors.

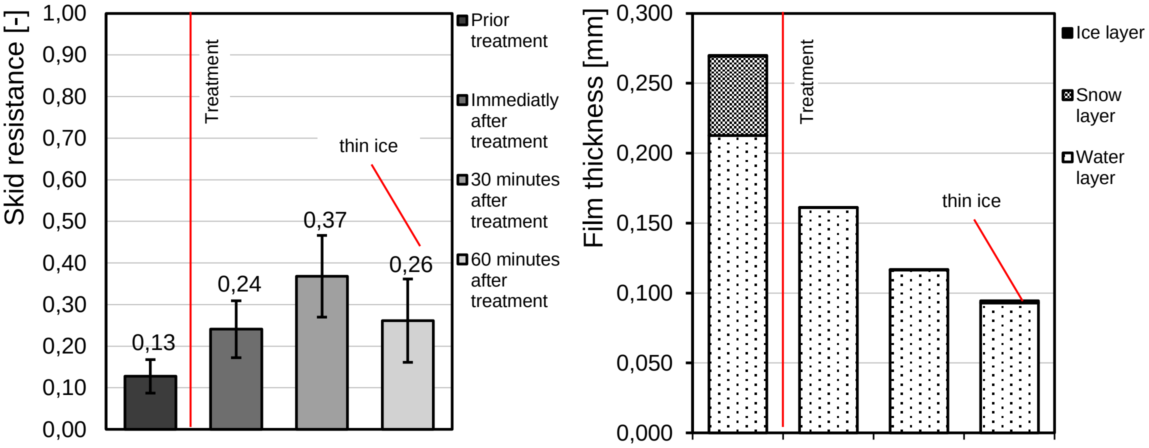


Fig. 16: (a) Development of skid resistance during winter maintenance (Griptester MKII)
(b) Corresponding structure, composition and film thickness (Optical device)

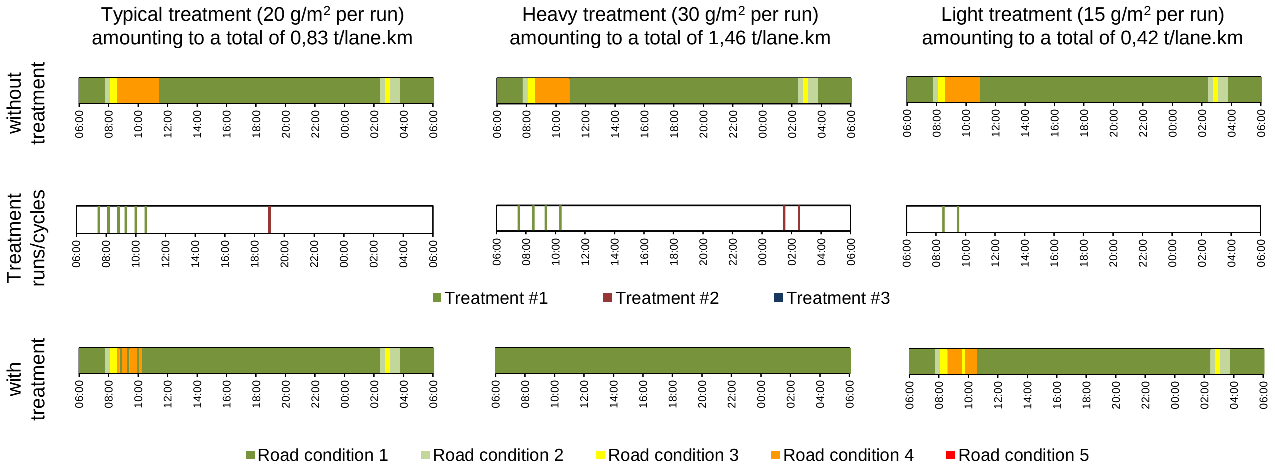
## 6. MODELING TREATMENT CYCLES AND ROAD SURFACE CONDITION

A simulation of different winter maintenance strategies on a highway section with 175 lane kilometers with 2 respectively 3 lanes per direction and a typical regional weather scenario shows the possibilities of the presented model. The typical weather scenario is chosen with snowfall from 07:00 am to 3:00 pm at a constant snowfall rate of 0.5 cm/h (equals 0.5 mm/h water) and hoarfrost in the early morning the next day. The calculated road conditions with and without treatment are compared in Figure 17.

As typical strategy a usual treatment is simulated, using 6 trucks for the entire highway section with an application rate of 20 g/m² in two treatment cycles starting 30 minutes after the beginning of the snowfall event and another treatment at shift change (7:00 pm). In this reference scenario 146 tons of salt were used, the total costs added up to 12,157 € with estimated time savings of 146 h for Cars and 34 h for trucks for the given traffic volume.

For the selected typical weather scenario it is also possible to provide better road conditions using higher application rates and adjust the timing of treatments. The amount of salt needed to provide road condition 1 almost all the time is 255 tons, almost double the number compared to the reference strategy. Doubling the amount of salting raises total winter maintenance costs only by 57% to 19,981 € due to fixed costs for personal and equipment. The time savings are almost doubled to 289 h for cars and 63 h for trucks. A more environmental friendly strategy with only 4 treatments at an application rate of 15 g/m² and a total salt consumption of 73 tons completes the treatment scenarios. In Figure 17 almost no improvement can be seen with the light treatment compared to no treatment due to the small time steps and limited impact. However there are still time savings of 46 h for cars and 11 h for trucks at maintenance costs of 6,900 € in this scenario.

In general most of the costs in winter maintenance are already predetermined due to the necessary resources to comply with legal obligations and minimum winter maintenance quality standards. Thus, most of the winter maintenance personnel and equipment has to be maintained either from road authorities or private contractors. The winter maintenance model allows a comparison of different winter maintenance strategies as well as the determination of optimal application rates for each individual situation.


Typical treatment (20 g/m² per run) amounting to a total of 0,83 t/lane.km

Heavy treatment (30 g/m² per run) amounting to a total of 1,46 t/lane.km

Light treatment (15 g/m² per run) amounting to a total of 0,42 t/lane.km

Fig. 17: Development of road conditions for two precipitation events during one day without treatment and with typical, heavy and light treatment strategies

## 7. CONCLUSIONS AND OUTLOOK

Faced with a growing demand in winter maintenance quality the personnel is in a difficult situation to decide about treatment intervals as well as application rates and timing. Based on the combined efforts of all regional road authorities in Austria as well as ASFiNAG and BMVIT a holistic model for winter maintenance was developed at the Vienna University of Technology. With this model the fundamental questions regarding timing and application rates as well as the resulting needs and impacts of treatment strategies can be answered.

With already existing road sensor equipment regarding temperature, residual salt and precipitation on the highway network of ASFiNAG in Austria as well as data from periodic condition surveys most key parameters for the winter maintenance model are already available. If the already existing real-time monitoring of winter maintenance vehicles is combined with a weather nowcasting and the presented holistic winter maintenance model a real-time calculation of road conditions becomes feasible.

Next possible steps include the implementation of the model in practical winter maintenance service on selected highway sections. With a real time operation of the model the questions regarding accuracy of results together with an identification of further development potential and possible improvements in road safety may be answered.

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